Hot Jupiters: Origins, Structure, Atmospheres

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Key Points:

- The origins of hot Jupiter exoplanets likely involve more than one formation pathway.
- Explanations for the anomalously large radii of hot Jupiters need a connection to atmospheric temperature.
- Hot Jupiters have complex atmospheres featuring ions, atoms, molecules, and condensates, where radiation and advection both play significant roles in controlling the 3D temperature structure.

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Abstract
We provide a brief review of many aspects of the planetary physics of hot Jupiters. Our aim is to cover most of the major areas of current study while providing the reader with additional references for more detailed follow-up. We first discuss giant planet formation and subsequent orbital evolution via disk-driven torques or dynamical interactions. More than one formation pathway is needed to understand the population. Next, we examine our current understanding of the evolutionary history and current interior structure of the planets, where we focus on bulk composition as well as viable models to explain the inflated radii of the population. Finally we discuss aspects of their atmospheres in the context of observations and 1D and 3D models, including atmospheric structure and escape, spectroscopic signatures, and complex atmospheric circulation. The major opacity sources in these atmospheres, including alkali metals, water vapor, and others, are discussed. We discuss physics that control the 3D atmospheric circulation and day-to-night temperature structures. We conclude by suggesting important future work for still-open questions.

Plain Language Summary

"Hot Jupiters" are gas giant planets, thought to be akin to Jupiter and Saturn, that orbit their parent stars with typical orbital periods of only a few days. These perplexing planets under strong stellar irradiation, found around 1% of Sun-like stars, have been extensively studied. Here we review many aspects of the physics of hot Jupiters. First, we discuss the leading scenarios for the formation and orbital evolution of the planets, including the dominant ideas that these planets originally form much further from their parent stars. Next, we describe models to assess their interior structure and thermal evolution and how strong stellar irradiation leads to radii that are significantly larger than that of Jupiter itself. Finally, we discuss many aspects of their atmospheres, including the opacity sources that control the temperature structure, the mass-loss processes that drive a planetary wind, and the dynamical processes that control atmospheric circulation and day-to-night temperature contrasts.

1 Discovery of Hot Jupiters

In 1995 Mayor & Queloz shocked the scientific world with the discovery of a Jupiter-mass planet, 51 Pegasi b, in a 4-day orbit around a Sunlike star, found via high-precision stellar radial velocity monitoring. Soon after, Butler et al. (1997) found additional close-in orbiting giant planets, and the astrophysical study of "hot Jupiter" exoplanets was born. While it had been suggested on theoretical grounds that planetary orbital migration could occur due to interaction with the planet-forming disk (Goldreich & Tremaine, 1980, Lin & Papaloizou, 1986), there was no particular prediction that gas giant planets could be found on such extreme orbits. There were immediate questions regarding all aspects of these planets, including their past and ongoing tidal evolution (Guillot et al., 1996, Trilling et al., 1998), pathways through which the planets could settle in so close to their stars (Lin et al., 1996, Rasio & Ford, 1996, Weidenschilling & Marzari, 1996), atmospheric composition (Seager & Sasselov, 1998), and how strong stellar forcing could alter the structure of the planets (Guillot et al., 1996) and lead to mass loss (Burrows & Lunine, 1995).

Five years later, the detection of the transits of planet HD 209458b (Charbonneau et al., 2000, Henry et al., 2000), brought forth a new era in the physics of hot Jupiters, since planetary radii and densities could now be measured. The detection of transits motivated researchers to set up wide-field ground-based surveys (Udalski et al., 2002, Bakos et al., 2005, Mandushev et al., 2005), to complement radial velocity detections and increase hot Jupiter detections. Those transiting planets found around relatively bright nearby stars have proven to be best for detailed atmospheric followup. Occurrence rate

studies from ground-based radial velocity and space-based transit surveys have revealed that of order 1/100 Sun-like stars host hot a Jupiter (e.g., Howard et al. 2012a, Wright et al. 2012). In this contribution we will first explore the origins of these planets, before examining planetary structure and evolution, and then moving on to atmospheres, along the way pointing towards the many open questions still in need of exploration.

2 Origins and orbital evolution

Over the past 25 years astronomers have made significant progress in understanding how hot Jupiters came to reside so close to their host stars. Here we summarize hypotheses for their origins (Section 2.1), constraints from orbital properties (Section 2.2) and stellar and companion (Section 2.3) properties, and take aways (Section 2.4).

2.1 Origins hypotheses

There are three main hypotheses for the origins of hot Jupiters: in situ formation, disk migration, and high eccentricity migration (Fig. 1). In situ formation posits that hot Jupiters grew or assembled their cores and accreted gaseous envelopes at their present day locations. Alternatively, hot Jupiters may have formed much further out and migrated through the gaseous disk that surrounds a young star. After the gas disk dissipates, a hot Jupiter far from its star could be disturbed onto a highly elliptical orbit and migrate through tidal dissipation. Investigations of hot Jupiters' origins have run parallel to those of giant planets in the Solar System, for which we also debate the roles of planetesimal (e.g., Malhotra 1993) and gas disk migration (e.g., Walsh et al. 2011) and scattering to elliptical orbits (e.g., Thommes et al. 1999). From a theory standpoint, all three mechanisms are viable but lead to different expectations for hot Jupiter properties.

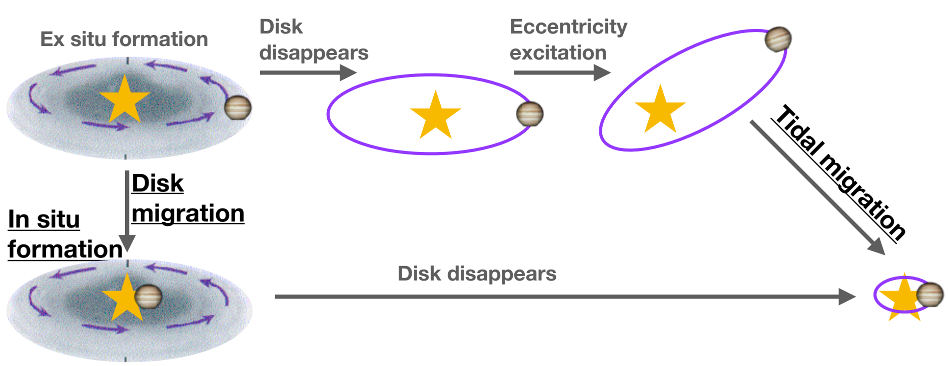


Figure 1. Origins hypotheses for hot Jupiters: in situ formation, disk migration, and high eccentricity tidal migration.

Giant planets are thought to form either by core accretion, in which a rocky protoplanet core accretes many times its mass in gas from the proto-planetary disk (e.g., Perri & Cameron 1974, Pollack et al. 1996; see Chabrier et al. 2014 for a review), or gravitational instability, in which part of the proto-planetary disk fragments into bound clumps (e.g., Boss 1997; see Durisen et al. 2007 for a review). Close to the star, gas conditions prevent formation by gravitational instability (Rafikov, 2005). Core accretion can operate close to the star (e.g., Lee et al. 2014, Batygin et al. 2016), but building a sufficiently large core ($\sim 10 M_{\oplus}$) is challenging. Feeding zones are small so the local available solids are insufficient (e.g., Schlichting 2014), mergers of multiple smaller cores are

prevented by the disk (e.g., Lee & Chiang 2016), and accretion of radially transported pebbles stalls at a much lower mass (see Johansen & Lambrechts 2017 for a review).

Hot Jupiters may form further out – where conditions for core accretion and/or gravitational instability are more achievable – and migrate in through torques from the gaseous disk (e.g., Goldreich & Tremaine 1980, Lin & Papaloizou 1986; Baruteau et al. 2014 review). The migration rate and direction are sensitive to disk conditions (e.g., Paardekooper & Mellema 2006, Duffell et al. 2014). If the planet reaches its short orbital period before the disk dissipates, it could be tidally disrupted or engulfed by the star. However, tidal interactions with the star (e.g., Trilling et al. 1998, Valsecchi et al. 2015) or stalling by a magnetocavity in the innermost disk (e.g., Rice et al. 2008, Chang et al. 2010) may preserve the hot Jupiter.

Tidal migration begins when a Jupiter is perturbed onto a highly elliptical orbit. Mechanisms include planet-planet scattering (e.g., Rasio & Ford 1996, Weidenschilling & Marzari 1996), cyclic secular interactions (e.g., Kozai-Lidov cycles; Kozai 1962, Lidov 1962, Wu & Murray 2003, Fabrycky & Tremaine 2007 see Naoz 2016 for a review), or chaotic secular interactions (e.g., Wu & Lithwick 2011). Tides raised by the star on the Jupiter shrink and circularize its orbit (e.g., Eggleton et al. 1998).

2.2 Constraints on origins hypotheses from orbital properties

Observed orbital properties of hot Jupiters can test hypotheses for their origins. They are found at host star separations where formation and migration can effectively deposit them, and their eccentricities and orbital alignment are relics of their orbital evolution. However, tidal effects complicate our interpretation of these properties.

Most hot Jupiters have typical orbital periods of ~ 3 days. For in situ formation, we expect hot Jupiters to be located at or beyond the disk edge, corresponding to ~ 10 days (e.g., Lee & Chiang 2017); therefore observed hot Jupiters are a factor of several closer to their stars than expected. Hot Jupiters may arrive through disk migration to half the corotation period, more consistent with hot Jupiters' observed orbital periods. High eccentricity tidal migration should deliver surviving planets at or beyond twice a_{Roche}, the tidal disruption limit. Although many hot Jupiters are beyond $2a_{\mathrm{Roche}}$, high eccentricity migration alone cannot easily account for those between 1–2 a_{Roche}. However, in all origins scenarios, hot Jupiters can later raise tides on their stars, further shrinking their semi-major axes (e.g., Jackson et al. 2008, Valsecchi et al. 2014).

Hot Jupiter eccentricities provide evidence that some arrived through the high eccentricity tidal migration channel. Out to $\sim$3 day orbital periods, most hot Jupiters have circular orbits; if these closest-in hot Jupiters ever had elliptical orbits, they would likely quickly tidally circularize because of the strong dependence of tidal dissipation on host star separation (e.g., Hut 1981). In the 3–10 day orbital period range, we observe a mixture of moderately elliptical ($0.2 < e < 0.6$) and circular orbits for hot Jupiters. If hot Jupiters form in situ or undergo disk migration, they would acquire these elliptical orbits at their present short orbital periods. However, proposed mechanisms for exciting eccentricities close to the star cannot account for many of the observed eccentricities (e.g., gas-disk interactions, Duffell & Chiang 2015; planet-planet scattering, Petrovich et al. 2014; secular forcing from an outer planet). Under the high eccentricity tidal migration hypothesis, moderately elliptical hot Jupiters are expected: they are in the process of tidal circularization. We may observe a mixture of circular and eccentric hot Jupiters at the same host star separations because of different timescales for the initial eccentricity excitation, diverse tidal dissipation properties, or multiple formation channels (i.e., a mix of high eccentricity tidal migration with disk migration and/or in situ formation).

Many hot Jupiters have orbits aligned to their host stars' spin, but others are severely misaligned (e.g., Albrecht et al. 2012 and references therein). Planets form in circumstellar disks, so we might naively expect hot Jupiters that originate in situ or via disk migration to keep their orbits aligned. In contrast, the gravitational interactions that trigger high eccentricity tidal migration can also misalign planets' orbits (e.g., Fabrycky & Tremaine 2007, Chatterjee et al. 2008). However, tidal interactions may realign the hot Jupiter (Winn, 2010a, Albrecht et al., 2012) – erasing evidence of high eccentricity tidal migration – and other physical processes can misalign the stellar spin from the circumstellar disk (e.g., Batygin 2012, Rogers et al. 2012, Storch et al. 2014), so that Jupiters form misaligned. Therefore spin-orbit alignments are not necessarily indicative of hot Jupiters' origins channel.

2.3 Constraints from stellar and companion properties

Characteristics of hot Jupiters' host stars and the presence and properties of planetary or stellar companions in the system can test theories for hot Jupiters' origins. The general giant planet occurrence rate increases with host star metallicity (Gonzalez, 1997, Santos et al., 2001, Fischer & Valenti, 2005), which is interpreted as solid-rich disks facilitating core accretion. There is some evidence that the correlation for hot Jupiters is even stronger (Jenkins et al., 2017), which most directly supports in situ formation (mitigating the challenge of forming a massive core close to the star) or high eccentricity migration triggered by a planetary companion (which may be more abundant in disks that nurture core accretion). Hosts of moderately eccentric hot Jupiters – which in Section 2.2 we attributed to high eccentricity migration – tend to have higher metallicities (Dawson & Murray-Clay, 2013).

Hot Jupiters have an occurrence rate of about 1% (e.g., Wright et al. 2012), which is about 10% of the overall giant planet occurrence rate (e.g., Cumming et al. 2008). The occurrence rate of hot Jupiters in the *Kepler* transit survey is about a factor of three lower than radial velocity surveys (Howard et al., 2012b, Wright et al., 2012). The discrepancy cannot be fully explained by differences in host star metallicity (Guo et al., 2017) but may be the result of an overall suppression of planet formation by close binaries in the *Kepler* sample (Moe & Kratter, 2019). High eccentricity tidal migration scenarios have not been demonstrated to be efficient enough to produce all hot Jupiters (e.g., Muñoz et al. 2016). The efficiencies of in situ formation and disk migration could be high enough but are dependent on uncertain disk conditions (e.g., Coleman & Nelson 2016, Lee & Chiang 2016).

Host star ages have the potential to distinguish the contributions of different origins channels: hot Jupiters that form in situ or migrate through the gas disk should already be present during the gas disk stage. In contrast, high eccentricity tidal migration typically operates after the gas disk stage, spawning hot Jupiters throughout a star's lifetime; however, timescales for eccentricity excitation and circularization enable most to arrive early. Therefore we expect hot Jupiters produced by high eccentricity migration to be largely absent during the gas disk stage and somewhat less common around younger stars than older stars. Measuring the contribution of high eccentricity tidal migration to the hot Jupiter population requires a sample of very young stars or a large sample of main sequence stars with precise ages. Recently two hot Jupiters were discovered around T Tauri stars, which are still in the gas disk stage (Donati et al., 2016, Yu et al., 2017). Ongoing T Tauri occurrence surveys will help evaluate what fraction of hot Jupiters must arrive during the gas disk stage.

In situ formation often leads to hot Jupiters with other planets nearby (e.g., Boley et al. 2016). Disk migration can deliver hot Jupiters in resonance with nearby planets (Malhotra, 1993, Lee & Peale, 2002) and/or with small planets that form nearby after the hot Jupiter's migration. In contrast, tidal migration destroys small planets within

the giant planet's initial orbit (e.g., Mustill et al. 2015). Hot Jupiters generally have an absence of nearby planets (Latham et al., 2011, Steffen et al., 2012), supporting the tidal migration hypothesis, but a notable exception is WASP-47b (Becker et al., 2015).

While high eccentricity migration initiated by planet-planet scattering could eject the other planet (e.g., Rasio & Ford 1996), secular eccentricity excitation retains the companion, which must have the right properties to have excited the eccentricity. Most hot Jupiters have planetary companions consistent with driven high eccentricity migration (Knutson et al., 2014, Bryan et al., 2016), but do not have a capable stellar companion (Ngo et al., 2016). These survey results point to fellow planets as the triggers of high eccentricity migration.

2.4 Summary

Multiple origins channels are needed to explain the observed range of orbital and companion properties for hot Jupiter. We refer readers to Dawson & Johnson (2018)'s review for a more detailed discussion of the evidence described here and constraints from radius inflation, atmospheric properties (e.g., Öberg et al. 2011, Madhusudhan et al. 2014), occurrence rates, and comparisons to warm Jupiters and smaller planets. High eccentricity tidal migration triggered by planet-planet secular interactions is likely one of the main origins channels, accounting for moderately eccentric hot Jupiters (and their increased host star metallicities), their general lack of small nearby planets, and the presence of distant planet companions capable of triggering high eccentricity migration. A second channel – disk migration or in situ formation – can supplement the inefficiency of producing hot Jupiters through tidal migration and account for hot Jupiters with rare small nearby planets, orbiting T Tauri stars and lower metallicity stars, and within 1–$2a_{\rm Roche}$ (without requiring subsequent tidal evolution).

3 Internal structure

Under intense stellar forcing, at a level of incident flux 10,000 times higher than Jupiter receives from the Sun, one may expect that the evolution of a hot Jupiter's interior structure may differ significantly compared to Jupiter itself. Indeed, it was suggested early on that hot Jupiters would not cool off as efficiently, leading to hotter interiors, and larger planetary radii, at old ages (Guillot et al., 1996). While this prediction has proven true, it is the magnitude of these very large radii, or the planetary *radius anomaly* that has proven difficult to understand. In this section, we introduce constraints on, and models for, the internal structure of hot Jupiters (see Baraffe et al., 2010, Fortney et al., 2010, and Baraffe et al., 2014 for detailed reviews in the context of giant planet structure and evolution, outside and inside the solar system). We describe the observed radius distribution of hot Jupiters in Section 3.1, proposed mechanisms to enhance the radii of hot Jupiters in Section 3.2, and the bulk composition of hot Jupiters in Section 3.3.

3.1 Radius anomaly

One can assess the observed radius distribution of hot Jupiters for clues regarding planetary structure. Figure 2, updated from Thorngren & Fortney (2018), shows planetary radii vs. incident stellar flux (bottom x-axis) and the zero Bond albedo equilibrium temperature (top x-axis). There is a clear rise in the distribution of radii, starting at $\sim 2{\times}10^{8}$ Gerg s^{-1} cm^{-2} in flux, or around 1000 K in equilibrium temperature. For comparison, planetary evolution model predictions for a 4.5 Gyr, pure H/He, 1 $M_{\rm J}$ planet that undergoes various levels of incident stellar flux are shown in the slowly rising dashed red curve. Many hot Jupiters hotter than the the $\sim$ 1000 K threshold have radii "above" the curve – this is the radius anomaly. Meanwhile, planets that lie below the red dashed

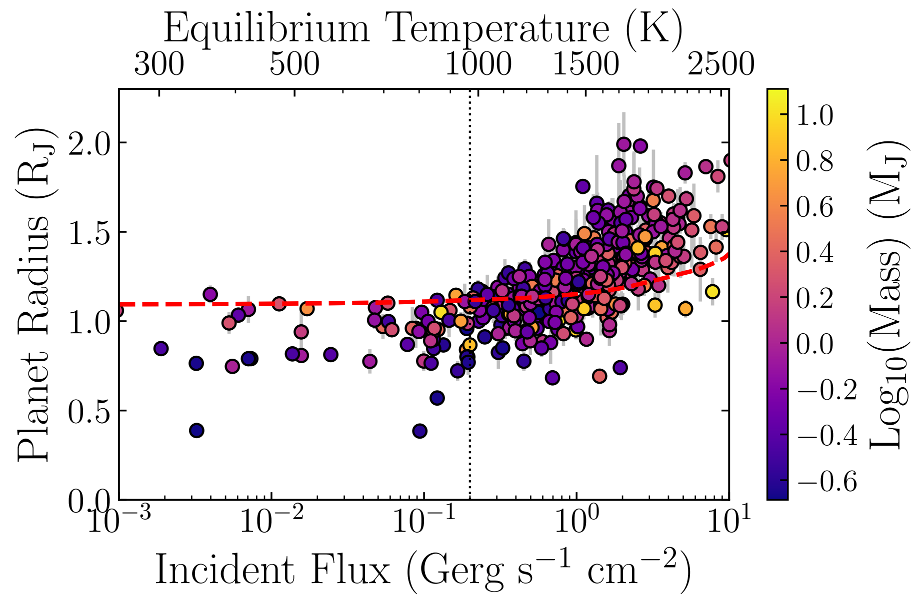


Figure 2. The observed radius of extrasolar gas giants (from 0.1 M_J to 13 M_J) plotted as a function of incident stellar flux and colored by planetary mass. The red dashed line shows an evolutionary model for a Jupiter-mass planet without any additional inflation effects at an age of 4.5 Gyr, and the vertical dashed line displays the flux cutoff below which no radius inflation is found. Figure courtesy of Daniel Thorngren.

curve likely just indicate planets that are relatively more enriched in heavy elements (Fortney et al., 2007, Burrows et al., 2007), often termed "metals" in an astrophysical context.

Figure 2 shows two important properties of the distribution of hot Jupiter radii that constrain models proposed to explain the radius anomaly (see Laughlin & Lissauer, 2015 and Laughlin, 2018 for recent reviews). First, Jupiter-mass planets that have equilibrium temperatures cooler than 1000 K (termed "warm Jupiters") are not observed to be inflated (Miller & Fortney, 2011, Demory & Seager, 2011, Laughlin et al., 2011). As a result, the mechanism(s) that cause the radius anomaly are likely not at work on these cooler Jupiters. Second, the radii of hot Jupiters appear to scale with their equilibrium temperature (Laughlin et al., 2011, Weiss et al., 2013, Thorngren & Fortney, 2018). This implies that the mechanism that causes the radius anomaly is linked to the incident flux from the host star.

Recent work has found avenues for better constraining the mechanism(s) that enhance radii. Thorngren & Fortney (2018) used a statistical analysis of hot Jupiter radii coupled to planetary structure models and found that the required conversion of incident flux to interior heating needed to explain the radius anomaly of the full sample of hot Jupiters peaks at an intermediate value of $T_{eq} \sim 1600$ K. Additionally, Hartman et al. (2016) found that the radii of hot Jupiters increase with increasing fractional main-sequence age of their host stars (and corresponding higher stellar luminosity as stars brighten on the main sequence), providing further evidence that the mechanism(s) that affect hot Jupiter radii are tied to the incident stellar flux. As predicted by Lopez & Fortney (2016), it has been found that planets that were warm Jupiters when their host stars were on the main sequence "re-inflate" as their host stars evolve off of the main sequence and their

equilibrium temperatures exceed 1000 K (Grunblatt et al., 2016, 2017, 2019). Further studies of both main-sequence and post-main-sequence re-inflation will improve constraints on the mechanism(s) that cause the radius anomaly of hot Jupiters (Komacek et al., 2020).

3.2 Proposed mechanisms to explain the observed radius distribution

A wide range of mechanisms have been proposed to explain the hot Jupiter radius anomaly (for previous summaries, see Weiss et al., 2013 and Baraffe et al., 2014). These mechanisms can be separated into two main categories: keeping the interior of the planet warm by reducing the rate of cooling to space, and utilizing incident stellar radiation or tidal energy to heat the planet from within.

3.2.1 Reduction of internal cooling

Gas giant planets are expected to form hot with large initial radii and contract over time as their interiors cool off. As a result, mechanisms that reduce the cooling rate of the planet can keep the interior hot. Because the interior temperature of a gas giant is directly linked to its radius (Hubbard, 1977, Arras & Bildsten, 2006, Ginzburg & Sari, 2015) reducing the interior cooling rate is equivalent to reducing the rate that the planet radius shrinks during its evolution. Gas giants cool off rapidly, and without a reduction in the cooling rate hot Jupiters would not appear inflated after $\sim$ Gyr of evolution (Guillot & Showman, 2002). Two mechanisms have been proposed to reduce the internal cooling. However, these mechanisms that rely on the reduction of cooling struggle to explain the increase in radius with increasing incident stellar flux shown in Figure 2.

The first mechanism to reduce the rate of cooling is invoking an enhanced atmospheric opacity that leads to longer timescales for radiative heat transport in the stably stratified envelope (Burrows et al., 2007). However, detailed calculations lead to only modest radius increases that cannot explain the entire population (Burrows et al., 2007). The second flavor of proposed mechanism to slow the cooling of hot Jupiters is for their interiors to not be fully convective, but experience double-diffusive layered convection (Chabrier & Baraffe, 2007, Kurokawa & Inutsuka, 2015). Double-diffusive convection occurs in the case of a molecular weight gradient that increases with increasing depth and stabilizes the envelope against convection. Both mechanisms above cannot explain the observed dependence of radius on incident flux for hot Jupiters. However semi-convection likely affects the interior evolution of a range of gas giant planets, as both Jupiter and Saturn experienced double-diffusive convection due to helium phase separation or post-formation composition gradients (Leconte & Chabrier, 2012, Nettelmann et al., 2015, Mankovich et al., 2016, Vazan et al., 2018).

3.2.2 Internal deposition of heat

Energy deposited into the interior of the planet can act to replace the cooling of the convective interior, reducing or even reversing the net loss of energy to space. The effect of internal heating on evolution is sensitive to both the depth and amount of energy deposited (Gu et al., 2004, Spiegel & Burrows, 2013, Komacek & Youdin, 2017), and only heating deep within the convective interior can fully offset interior cooling (Guillot & Showman, 2002). There are two classes of deposited heating mechanisms: tidal dissipation and conversion of incident stellar flux to deposited heat.

Tidal dissipation was the first mechanism proposed to heat the interior of hot Jupiters (Bodenheimer et al., 2001). Two types of mechanisms have been proposed to lead to tidal heating of hot Jupiters. The first is eccentricity tides due to the tidal circularization of hot Jupiters that formed through high eccentricity migration (Bodenheimer et al., 2001, Gu et al., 2003, Jackson et al., 2008, Ibgui & Burrows, 2009). It is unlikely that eccen-

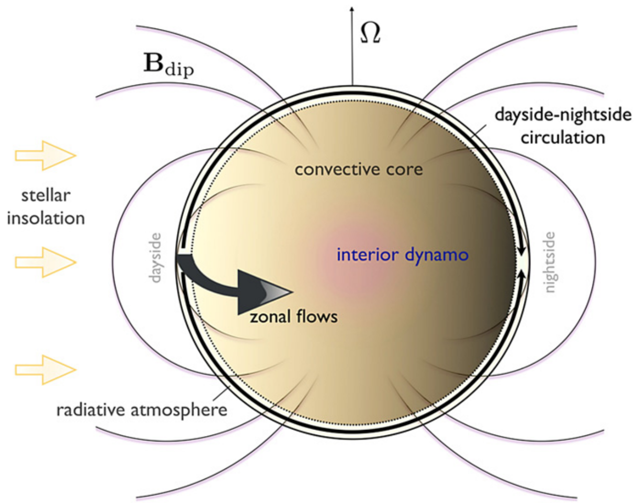


Figure 3. Schematic diagram showing the coupling between the atmospheric circulation and interior magnetic field of hot Jupiters. From Batygin et al. (2013).

tricity tides can explain the inflated radii of all hot Jupiters, but they may play a key role for certain systems (Miller et al., 2009, Leconte et al., 2010).

The second type of tidal heating mechanism is thermal tides, which are tides driven by the spatial and temporal inhomogeneity of atmospheric column mass (which is linked to temperature), originally proposed to explain the slow spin rate of Venus (Gold & Soter, 1969). These atmospheric tides transfer angular momentum and energy from the orbit to the planetary rotation (Thompson, 1882), increasing the rotation rate and pushing hot Jupiters away from a synchronous state, leading to gravitational tidal dissipation. Thermal tides have been shown to provide a sufficient rotational perturbation and resulting dissipation to explain the radius anomaly (Arras & Socrates, 2010, Socrates, 2013), but the depth at which thermal tides deposit heat is uncertain (Gu et al., 2019).

The second class of mechanism proposed to heat hot Jupiters relies on converting a fraction of the incident stellar flux into deposited heating. Shear instabilities in the deep atmosphere leading to deposited heat were the first of this class to be considered, and rely on dissipation of the $\sim$ km s^{-1} winds in hot Jupiters (see Section 4) through fluid dynamic instabilities at interfaces where the winds quickly decay (Guillot & Showman, 2002, Bodenheimer et al., 2003). Another mechanism relating to the atmospheric circulation is large-scale vertical mixing in the deep atmosphere acting to force a downward heat flux that carries a fraction of incident stellar power to higher pressures, where it can affect the interior evolution (Youdin & Mitchell, 2010, Tremblin et al., 2017, Sainsbury-Martinez et al., 2019).

As the atmospheres of hot Jupiters are hot enough that species with low ionization potentials (e.g., Na, K) are partially ionized, Batygin & Stevenson (2010) proposed that the atmospheric current driven by the fast motions of a partially ionized fluid can penetrate into the interior of the planet, leading to "Ohmic dissipation" (i.e., electrical resistive heating) at depth. A variety of studies have examined Ohmic dissipation and found varying degrees of success in explaining the radius anomaly (e.g., Perna et al., 2010b, Batygin et al., 2011, Huang & Cumming, 2012, Menou, 2012, Rauscher & Menou, 2013, Wu & Lithwick, 2013, Rogers & Komacek, 2014, Ginzburg & Sari, 2016). Hot Jupiters are expected to have strong internal magnetic fields (Yadav & Thorngren, 2017, Cauley et al., 2019), which couple with the atmospheric currents to induce magnetic forces that

act against the circulation (see Figure 3). These magnetic effects naturally reduce the Ohmic dissipation rate for hot planets with equilibrium temperatures $\gtrsim$ 1500 K (Menou, 2012, Rogers & Komacek, 2014, Ginzburg & Sari, 2016), in agreement with the findings of Thorngren & Fortney (2018). However, Ohmic dissipation is not thought to provide sufficiently deep heating to lead to re-inflation (Wu & Lithwick, 2013, Ginzburg & Sari, 2016).

While more work is required to fully determine the heating mechanism(s) that cause the radius anomaly of hot Jupiters, Thorngren & Fortney (2018) have shown that the additional radius inflation power has a characteristic magnitude as a function of incident flux. This strongly suggests that mechanisms in the three proceeding paragraphs, that are coupled to this stellar heating, including thermal tides, shear instabilities or vertical mixing, and Ohmic dissipation, are the key contenders. Indeed, very recently Sarkis et al. (2020) have suggested that multiple mechanisms must be at play to explain the population.

3.3 Bulk planetary metallicities

While significant theoretical work has gone into examining mechanisms that lead to large radii and low densities for this class of planets, much less work has gone into understanding planets that are not inflated, or are "over-dense." The discovery of HD 149026b (Sato et al., 2005), with a very high density compared to other known transiting planets at that time, suggested that the planet must be more metal-rich than Jupiter and Saturn (Sato et al., 2005, Fortney et al., 2006, Burrows et al., 2007). The fact that the planet's parent star is quite metal-rich led to the first discussion of a potential star-planet composition connection (Guillot et al., 2006).

Only relatively recently has a large enough sample size of transiting giant planets become available that the bulk metallicities of the planets (as diagnosed from a combination of their bulk densities and planet thermal evolution models) can be evaluated. Thorngren et al. (2016), following up on preliminary work of Miller & Fortney (2011), find a clear relation between giant planet mass and bulk metallicity. This both confirms a key prediction of core-accretion planet formation (Mordasini et al., 2014), in a generic sense, but also gives a well-defined slope and scatter to this relation that future models of planet formation must aim to reproduce. The more massive giant planets are less metal-rich (reproducing the solar system's trend), but the amount of metals within planets more massive than Jupiter is surprising, suggesting that massive "super-Jupiters" may often accrete well over 100 $M_\oplus$ of metals. A recent new spin on this work is that the metal-richness of the planets does *not* appear to correlate with the metallicity of the parent star (Teske et al., 2019).

These kinds of investigations to assess bulk composition are entirely complementary to studies of hot Jupiter atmospheres, where one seeks the abundances of particular atoms and molecules. Interior structure and evolution modeling has the advantage of having a larger sample size to examine, and it does not require further characterization observations. However, these atmospheric abundance details are potentially a treasure trove of information, and it is to atmospheres that we next turn.

4 Atmospheres

The atmospheres of hot Jupiters lie in a unique thermal, chemical, and dynamical regime characterized by strong incident radiation, large horizontal temperature contrasts, species in the ionic, atomic, molecular, and condensate phases, and fast winds that approach or exceed the speed of sound. Due to their large radii and hot temperatures, hot Jupiters host the only class of exoplanet atmosphere that can currently be observationally characterized in detail with spectroscopic observations over an entire orbital phase.

These observations serve as a testbed for models of hot Jupiter atmospheres, which have largely been successful in explaining the large-scale observed climate of hot Jupiters. Here we describe observational characterization of hot Jupiter atmospheres in Section 4.1, summarize our understanding of the atmospheric structure of hot Jupiters in Section 4.2, and describe theory for and modeling of the atmospheric circulation of hot Jupiters in Section 4.3.

4.1 Observational characterization

Observations of hot Jupiter atmospheres have been an exciting aspect of exoplanet science over nearly two decades. Much of this work has utilized the *Hubble* and *Spitzer* Space Telescopes, which were designed and built before the dawn of the exoplanet atmosphere era. Observers have needed to be extremely creative and resourceful to use these telescopes for high precision photometry and spectroscopy. See Winn (2010b), Crossfield (2015), Sing (2018), and Deming et al. (2019) for a comprehensive introduction and review of these characterization techniques. In the past decade high-resolution atmospheric characterization from the ground has been enabled with spectrographs on the world's largest telescopes, which is covered in more detail in Birkby (2018) and Brogi & Line (2019).

4.1.1 Transmission spectroscopy

Transmission spectroscopy was the first method used to characterize transiting planet atmospheres, and was first modeled by Seager & Sasselov (2000), Brown (2001), and Hubbard et al. (2001) and was observed by Charbonneau et al. (2002) with *Hubble* for HD 209458b. With this method, during the transit some flux from the parent star passes through the planet's thin outer atmosphere, imprinting small planetary absorption features on the stellar spectrum, during the transit. Precisions of 10^{-4} are necessary, as the area of the annulus of planetary atmosphere is $\sim 0.01\times$ the area of the planet, which is again $\sim 0.01\times$ the area of the star.

In transmission, atomic metals have been observed in the UV and the optical, with previous Na and K detections (Charbonneau et al., 2002, Redfield et al., 2008, Sing et al., 2011, Nikolov et al., 2014, Sing et al., 2015, Wyttenbach et al., 2015) due to these species having particularly prominent features at 589 nm and 770 nm, respectively. The presence of these strong, very pressure broadened optical features give rise to the very low geometric albedos measured and inferred for hot Jupiters, often below 0.1 (Esteves et al., 2015, Parmentier et al., 2016), which is much lower than Jupiter's ~0.5. In the near-IR, *Hubble*'s Wide-Field Camera 3 sits atop a water band from 1.1 to 1.7 μm, which has allowed for water vapor detections in many objects (Deming et al., 2013, Huitson et al., 2013, Kreidberg et al., 2014, McCullough et al., 2014, Kreidberg et al., 2015, Line et al., 2016, Sing et al., 2016) (see Kreidberg, 2017 for a recent review covering molecular abundance constraints) with the signal-to-noise ratio sometimes high enough to determine the water mixing ratio. *Spitzer* allowed for photometry in the 3.6 μm and 4.5 μm bands, which has suggested roles for CO and CO_2 absorption in the 4.5 μm band (Désert et al., 2009, Madhusudhan, Harrington, et al., 2011, Stevenson et al., 2017).

Transmission spectroscopy at higher resolution has yielded information on atmospheric dynamics, as subtle Doppler shifts of absorption lines can be used to assess the velocity and direction of atmospheric flow (Miller-Ricci Kempton et al., 2012, Showman et al., 2013, Flowers et al., 2019). This has enabled planetary-scale wind determinations (Snellen et al., 2010), differential wind measurements between leading and trailing hemispheres (e.g., Louden & Wheatley, 2015), and constraints on the planetary rotation rate (Brogi et al., 2016). Ehrenreich et al. (2020) found evidence for strong (≈ 5.3 km s^{-1}) day-night winds in the ultra-hot Jupiter WASP-76b, along with evidence for condensation of iron on the planetary nightside due to a hemispheric asymmetry in its absorption signal. Recently, Tabernero et al. (2020) confirmed this detection of day-night winds

for WASP-76b over a broader range of atomic and molecular signatures, including ionized calcium, atomic manganese, magnesium, sodium, potassium, and lithium. These are just a handful of the broad range of atomic and ionized metallic species and molecules that have been detected in hot and ultra-hot Jupiter atmospheres with high-resolution transmission spectroscopy (e.g., Birkby et al., 2013, Brogi et al., 2014, Birkby et al., 2017, Nugroho et al., 2017, Piskorz et al., 2017, Wyttenbach et al., 2017, Hoeijmakers et al., 2018, Seidel et al., 2019, Hoeijmakers et al., 2020, for a recent review see Birkby, 2018).

4.1.2 Transmission spectroscopy and atmospheric escape

A special case of transmission spectroscopy, including studies at both low (via *Hubble*) and high resolution (from the ground), is the study of atmospheric escape from hot Jupiters. The high X-ray and UV fluxes are typically absorbed by hydrogen and metals, via photoionization, quite high in the planetary atmosphere (the thermosphere), where infrared opacities are low and cooling is inefficient, such that temperatures can reach $\sim 10^4$ K. This can drive a hydrodynamic flow that can become unbound from the planet. The amount of escape driven by this heating depends on how quickly the thermosphere cools through collisionally-excited atomic lines. Mass loss is considerable, and hot Jupiters may typically lose $\sim 1\%$ of their total mass, particularly at young ages when XUV fluxes are highest.

After nearly 20 years of observations (Vidal-Madjar et al., 2003, 2004, Ehrenreich et al., 2015) and theory (Yelle, 2004, Murray-Clay et al., 2008, Owen & Adams, 2014) a considerable literature has developed. A recent review can be found in Owen (2019). Escaping hydrogen has been found from both Lyman-α observations (Vidal-Madjar et al., 2003, Lecavelier Des Etangs et al., 2010) and observations of the hydrogen Balmer series (Jensen et al., 2018, Cabot et al., 2020, Wyttenbach et al., 2020, Yan et al., 2020). Of particular recent interest has been the detection of escaping neutral helium (Spake et al., 2018, Ninan et al., 2020) via the 1083 nm triplet. This helium is presumably a part of the bulk flow from the planets (Oklopčić & Hirata, 2018). The combination of more detailed modeling studies (Oklopčić et al., 2020) and high-spectral resolution observations from ground-based telescopes that resolve velocity information for the He triplet (Allart et al., 2019) make this an important area for growth.

4.1.3 Emission spectroscopy

As the name implies, hot Jupiters are "hot" and hence have substantial thermal emission. For transiting planets, at the planetary occultation, or secondary eclipse, the planet passes behind the parent star. The combined amount of star+planet flux decreases for the duration of the occultation, as the planet is blocked from view. The power of emission spectroscopy, in principle, is that one could learn about atmospheric abundances (as in transmission spectroscopy) but also about the atmosphere's temperature structure, which is typically quite difficult to probe in transmission.

The first emission detections were by Deming et al. (2005) and Charbonneau et al. (2005) for HD 209458b and TrES-1b, respectively. Over the years, particularly in the Warm *Spitzer* extended mission, large samples of 2-band emission photometry at 3.6 and 4.5 μm was obtained for dozens of planets. These growing samples are now being assessed for trends that may suggest changes in atmospheric chemistry or temperature structure, as a function of the stellar incident flux (Wallack et al., 2019, Garhart et al., 2020, Baxter et al., 2020), as shown in Figure 4. Furthermore, the idea of "eclipse mapping" uses differences in time-resolved ingress and egress lightcurves to create a brightness map, with latitude and longitude information, across the full day-side of the transiting planet (Rauscher et al., 2007, Majeau et al., 2012, De Wit et al., 2012).

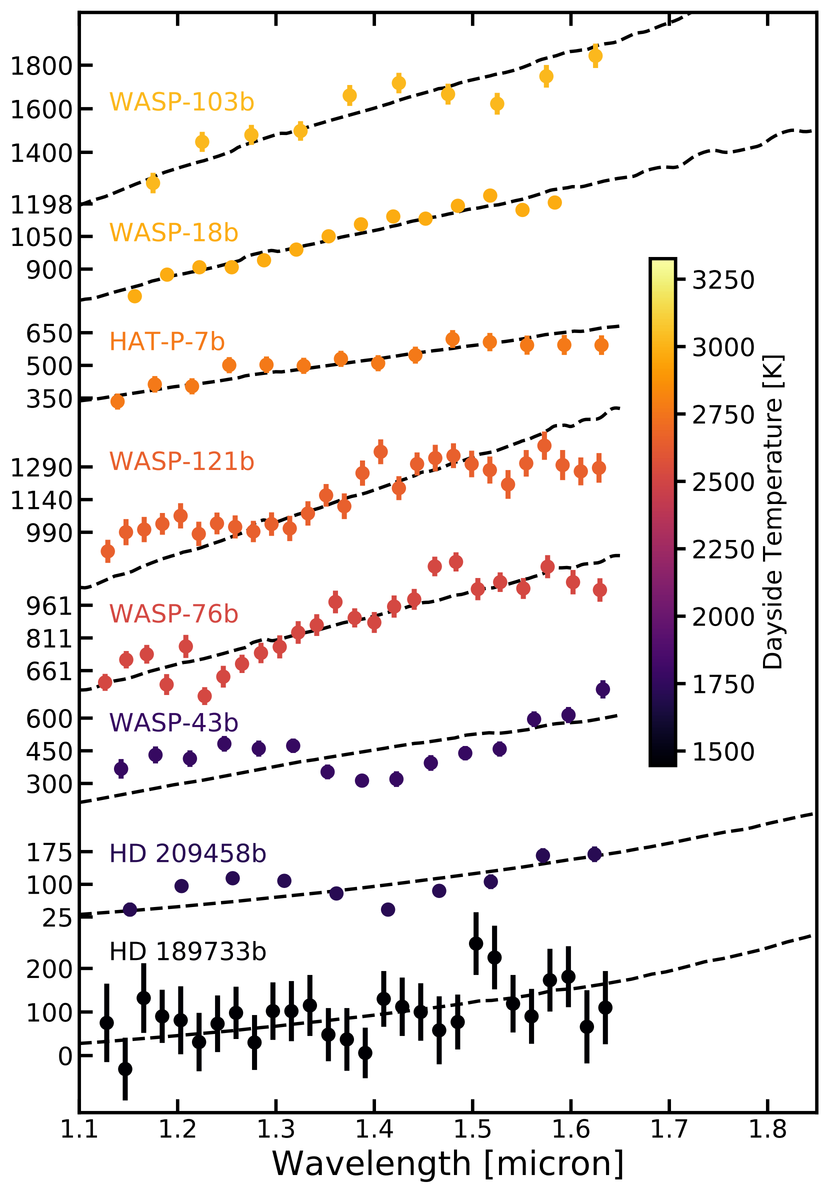


Figure 4. *HST/WFC3* secondary eclipse spectra of hot and ultra-hot Jupiters observed in spatial scan mode as a function of dayside temperature. With increasing temperature, the 1.4μm water vapor absorption feature clearly seen for WASP-43b becomes diminished. In some cases (e.g., WASP-121b), this water feature can be seen in emission, indicative of an inverted temperature profile. Figure courtesy of Megan Mansfield.

Recently, it was discovered that the emission spectra of ultra-hot Jupiters are distinct from those of cooler hot Jupiters. *HST/WFC3* emission spectra from a wide range of ultra-hot Jupiters (e.g., Stevenson, Bean, et al., 2014, Haynes et al., 2015, Beatty et al., 2017, Evans et al., 2017, Arcangeli et al., 2018, Kreidberg et al., 2018, Mansfield et al., 2018, Baxter et al., 2020, Fu et al., 2020, Mikal-Evans et al., 2020) show black-body like, almost featureless spectra, with much weaker water features than are commonly found for cooler hot Jupiters (see Figure 4). It has been suggested that the almost featureless emission spectra of ultra-hot Jupiters is due to the dissociation of water molecules at the high temperatures on their daysides in concert with the formation of H^-, which acts as a strong continuum opacity source (Kitzmann et al., 2018, Lothringer et al., 2018, Parmentier et al., 2018). Additionally, *Spitzer* photometry has shown that the ultra-hot Jupiters generally have stratospheres with inverted temperature-pressure profiles (potentially due to TiO/VO), while cooler hot Jupiters do not host inversions (Garhart et al., 2020, Baxter et al., 2020). These observed differences in the atmospheric composition and thermal structure between hot and ultra-hot Jupiters has led to the understanding that ultra-hot Jupiters represent a distinct class of exoplanet from cooler hot Jupiters.

4.1.4 Phase curves

Not long after the first detection of thermal emission from hot Jupiters, it was suggested that obtaining a phase curve of thermal emission over part of or all of a planetary orbit would be diagnostic of day-to-night temperature contrast and hot-spot offsets, first predicted in Showman & Guillot (2002). Knutson et al. (2007) published a half-orbit phase curve at 8 μm for planet HD 189733b, validating several aspects of these general circulation models. This paper, and later Cowan et al. (2009), described how phase curves could be inverted to understanding planetary brightness vs. longitude. Phase curves for eccentric hot Jupiters, which are rare, are especially valuable as they show the planet's response near periapse, including the timescale of heating and subsequent cooling of the planetary atmosphere (Laughlin et al., 2011, Lewis et al., 2013, de Wit et al., 2016).

The first spectroscopic phase curve was of the planet WASP-43b (Stevenson et al., 2014) with *Hubble* from 1.1 to 1.7 μm. Importantly, it allowed one to probe atmospheric conditions and the hot-spot offset as a function of atmospheric depth, as observations within the water band at 1.4 μm probe less-deeply into the atmosphere than neighboring wavelengths with lower opacity.

4.2 Temperature structure, clouds, and composition

The temperature structure of the planetary atmosphere is sensitive to many factors, including the absorption of stellar flux as a function of depth and wavelength, the emission of the absorbed flux and any intrinsic flux as a function of depth, and wavelength, and advection of energy to cooler parts of the atmosphere, including the night side. This is a complex problem and a variety of 1D, 2D, and 3D models have been brought to bear.

Figure 5 shows a sampling of 1D atmospheric pressure-temperature (P–T) profiles for metal-enriched (10× solar, or Saturn-like) atmospheres at small orbital distances. The hottest models show a relatively shallow radiative-convective boundary (RCB) due to the high internal fluxes from whatever mechanism causes the radius anomaly (Thorngren et al., 2019). For slightly cooler planets the RCB may reach $\sim$ 1 kbar.

The potential for gaseous TiO and VO, which dominate the optical spectra of M stars, to be found in the hottest hot Jupiters deserves a specific mention. Hubeny et al. (2003) suggested that the high opacity of TiO and VO at low pressure, coupled with the lower opacity of coolants like water vapor, may drive a temperature inversion in these planets, which is not shown in Figure 5. Fortney et al. (2008) extended this work and

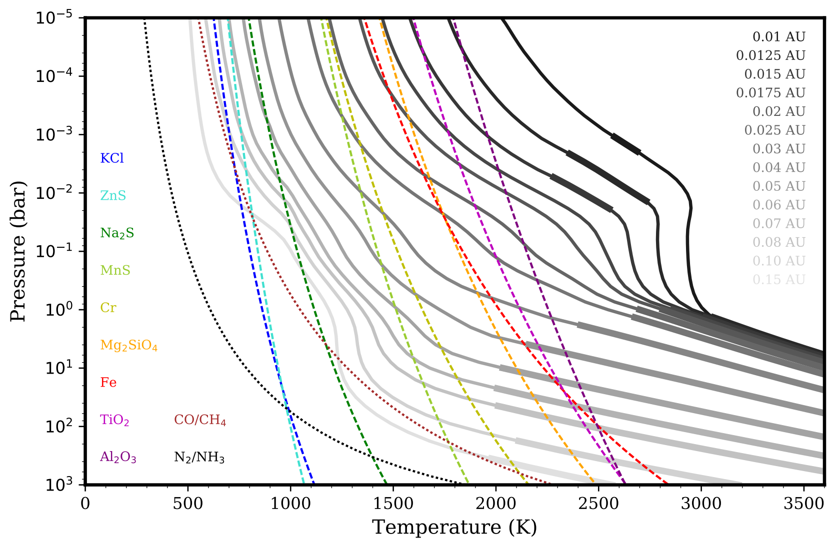


Figure 5. Atmospheric P–T profiles as a function of distance from the Sun. Thicker lines show convective regions and thinner lines show radiative regions. Cloud condensation curves for relevant condensates are shown with colored dashed curves. The equal-abundance curves of CO/CH_4 and N_2/NH_3 are shown with colored dotted curves. Figure courtesy of Peter Gao.

suggest classifying planets in equilibrium temperature based on the presence or absence of TiO/VO. The role of TiO/VO in these hottest atmospheres is still not clear, since these heavy molecules could be difficult to mix into the upper atmosphere, or could be lost into refractory clouds on the planetary night (Spiegel et al., 2009, Parmentier et al., 2013). Significant additional work has gone to understand other aspects of how atmospheric chemistry and incident stellar flux changes the temperature structure, atmospheric abundances, and resulting spectra (e.g., Madhusudhan, Mousis, et al., 2011, Mollière et al., 2015, Lothringer et al., 2018).

The equilibrium chemistry of these hot atmospheres has been explored by a number of authors, sometimes in conjunction with brown dwarf chemistry over this same P–T space (Lodders, 1999, Lodders & Fegley, 2002, Visscher et al., 2010, Madhusudhan, Mousis, et al., 2011, Blecic et al., 2016, Woitke et al., 2018). Figure 5 shows the equal-abundance curves for CO/CH_4 (dashed red) and N_2/NH_3 (dashed black), showing the epectation that the dominant carbon carrier for hot Jupiters is CO, the dominant nitrogen carrier is N_2, and oxygen is mostly found in CO and H_2O. A variety of atomic metals are found in the vapor phase, such as Na and K, which can dominated the optical opacity over a wide temperature range (Sudarsky et al., 2003). For the hottest profiles, abundances can be more akin to M-type (or even late K) stars, leading to even more atomic metals present in the ultra-hot Jupiters (Kitzmann et al., 2018).

Studies of kinetic chemistry and photochemistry in hot Jupiters include Zahnle et al. (2009), Moses et al. (2011), Venot et al. (2012), Tsai et al. (2017), Hobbs et al. (2019), Venot et al. (2020), and others. Kinetic effects include the relevant chemical conversion and mixing timescales for these atmospheres. Thorngren et al. (2019) and Fortney et al. (2020) have stressed that understanding the temperature structure of the (not visible) deep atmosphere, from thermal evolution models, is important for understanding these timescales and the associated atmospheric abundances. Products that are typically enhanced compared to equilibrium chemistry, due to a variety of kinetic and photochemical effects, are molecules such as HCN, C_2H_2, and CO_2.

Within the framework of chemistry calculations, a wide range of refractory clouds were long expected to be found in hot Jupiter atmospheres (Marley et al., 1999, Sudarsky et al., 2000), in particular Mg-bearing silicates and iron, as shown in Figure 5. The chemistry of this condensation sequence is now reasonably well understood from the atmospheres of brown dwarfs over this similar temperature range (Ackerman & Marley, 2001, Helling & Casewell, 2014). One important aspect of the formation of condensates is that due to the loss of some elements from the gas phase, as they are sequestered in condensates, the atmospheric chemistry of remaining gases can be altered compared to simple expectations (Lodders & Fegley, 2002, Helling, 2019). Observationally, Sing et al. (2016) demonstrated the near-ubiquity of clouds in affecting transmission spectra, which is well matched by models that include silicate clouds (Gao et al., 2020). However, the role of clouds in emission spectra is lacking in data, and the role in phase-dependent reflection spectra is still emerging (Heng & Demory, 2013, Esteves et al., 2015, Hu et al., 2015, Oreshenko et al., 2016, Parmentier et al., 2016, Roman & Rauscher, 2017). Significant ongoing theoretical work is underway in combining 3D circulation models with cloud particle formation and transport, as discussed in Section 4.3.1.

The high atmospheric temperatures of hot Jupiters, compared to our solar system's giant planets, make them fantastic laboratories for unveiling giant planet atmospheric abundances, as nearly all volatile species should be found in the vapor phase, rather than sequestered into clouds. Öberg et al. (2011) and Fortney et al. (2013) have suggested links between atmospheric abundances and giant planet formation, the former in terms of carbon-to-oxygen (C/O) ratios, and the latter in terms of overall metallicity enhancements. These ideas have been greatly developed by additional models, including Madhusudhan et al. (2014), Mordasini et al. (2016), and Cridland et al. (2019). The observational determination of C/O ratios have been hampered by the limited bandpass for *Hubble* spectroscopy. The determination of atmospheric metallicities, as a function of planet mass, began with Kreidberg et al. (2014) for the planet WASP-43b. Error bars on abundance determinations with current instruments have been large, and there are not necessarily robust trends in metal-enrichment as a function of planet mass (Fisher & Heng, 2018, Welbanks et al., 2019). A recent compilation of atmospheric abundances is shown in Figure 6 from Welbanks et al. (2019).

Several frameworks for simultaneously retrieving atmospheric abundances and temperature structure in a Bayesian framework, termed "retrieval," are essential to this work, build on solar system heritage (Irwin et al., 2008, Line et al., 2013), and are reviewed in Madhusudhan (2018) and Barstow & Heng (2020). More comprehensive reviews of hot Jupiter models and their comparison with data can be found in Madhusudhan et al. (2016), Helling (2019), and Madhusudhan (2019).

4.3 Atmospheric circulation

4.3.1 Numerical simulations

Over the past two decades, a wide range of general circulation models (GCMs) have been developed to simulate the atmospheric circulation of hot Jupiters. GCMs solve the dynamical equations of fluid motion coupled to a radiative transfer model that determines the radiative heating/cooling rate. The reader is referred to Showman et al. (2010), a detailed review of exoplanet atmospheric fluid dynamics, to Heng & Showman (2015) (see their Table 1) for a review of established hot Jupiter GCMs, to Showman et al. (2020) for a review of recent advances in the study of hot gas giant exoplanets, and to X. Zhang (2020) for an expansive review of the atmospheric circulation regimes of exoplanets. Many hot Jupiter GCMs solve the primitive equations of meteorology (e.g. Showman & Guillot, 2002, Menou & Rauscher, 2009, Rauscher & Menou, 2010, Heng et al., 2011, Lewis et al., 2014, Polichtchouk et al., 2014, Kataria et al., 2015, Carone et al., 2019), which are a simplified form of the Navier-Stokes equations relevant to thin, locally hydrostatic

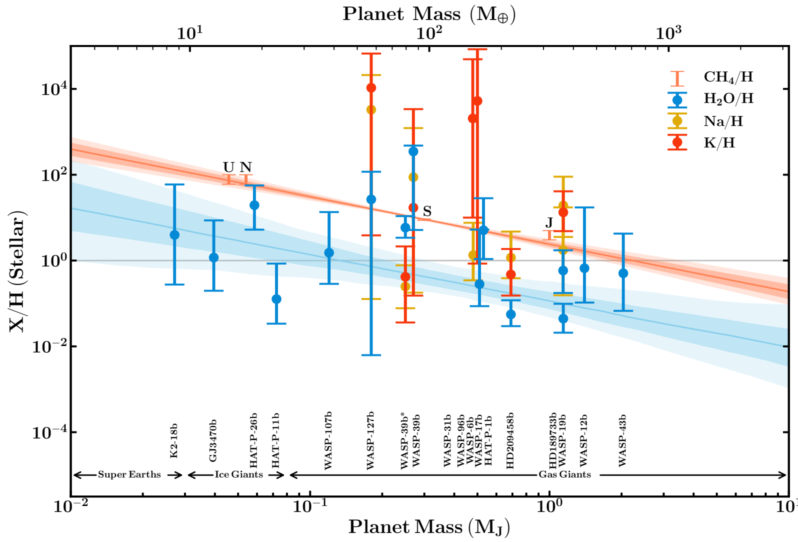


Figure 6. Abundances of atoms and molecules in the atmospheres of hot Jupiters (and hot Neptunes) from Welbanks et al. (2019). The solar system mass-atmospheric metallicity trend, based on CH_4 is clear, shown in orange. A similar trend *may* be emerging for H_2O in hot Jupiters, but with a lower mixing ratio.

atmospheres (Vallis, 2006, Holton & Hakim, 2013). A subset of models solve the non-hydrostatic Euler or Navier-Stokes equation sets (e.g., Dobbs-Dixon & Agol, 2013, Mayne et al., 2014, Mendonça et al., 2016) that capture the propagation of sound waves, which is important because the winds in hot Jupiter atmospheres can approach or exceed the speed of sound.

Though hot Jupiter GCMs have quantitative differences in atmospheric climate and wind speeds, they show qualitatively similar large-scale atmospheric circulation patterns (see Figure 9 of Heng & Showman, 2015). GCMs find that the atmospheric circulations of hot Jupiters are characterized by large dayside-to-nightside temperature contrasts. The large dayside-to-nightside temperature gradient forces fast winds which manifest as eastward (propagating in the direction of rotation) jets with maximum speeds in equatorial regions (Showman & Polvani, 2011, Tsai et al., 2014, Hammond & Pierrehumbert, 2018). These fast winds lead to a shift in the temperature maximum (or "hot spot") eastward (downwind) of the substellar point. The strong eastward flow near the equator of hot Jupiters is known as "superrotation" because the angular momentum of the atmospheric circulation exceeds the rotational angular momentum of the interior of the planet (Vallis, 2019).

Even though the overarching picture of hot Jupiter atmospheres has remained unchanged since Showman & Guillot (2002), there are many new frontiers that models are currently exploring. Cloud formation and evolution can have important radiative impacts on climate and observable properties (Helling et al., 2016, Wakeford et al., 2017, Powell et al., 2018, Gao et al., 2020), which can feed back onto atmospheric dynamics. Recent modeling efforts (e.g., Lee et al., 2016, Lines et al., 2018, 2019, Roman & Rauscher, 2019, Parmentier et al., 2020, Roman et al., 2020) have shown that cloud-radiative feedbacks can affect the climate and observable properties of hot Jupiters. Due to winds transporting species before they can relax to chemical equilibrium, the effects of chemical disequilibrium are expected to impact the atmospheric composition and observable properties of hot Jupiters (Cooper & Showman, 2006, Drummond et al., 2018, Zhang & Show-

man, 2018, Mendonça et al., 2018, Steinrueck et al., 2019). It is also expected that magneto-hydro-dynamic (MHD) effects play a role in the circulation of hot Jupiters. A wide range of efforts have included MHD effects in GCMs of hot Jupiter atmospheres (e.g., Perna et al., 2010a, Batygin et al., 2013, Rauscher & Menou, 2013, Rogers & Showman, 2014), and have shown that MHD can impact the strength and even direction of the equatorial jet. Due to the strong spatial dependence of winds, it is expected that shear instabilities and shocks play a role in the dissipation of the circulation of hot Jupiters (J. Li & Goodman, 2010, Heng, 2012, Perna et al., 2012, Fromang et al., 2016), but high-resolution non-hydrostatic global models are required to fully assess the impact of instabilities and shocks on the circulation. Additionally, long integration timescales are needed to properly model the impact of the deep atmospheric circulation of hot Jupiters on observable levels, as the timescale for radiative adjustment of the deep atmospheric layers is thousands of years at the ~ 100 bar pressures at the base of typical GCM models (Arras & Bildsten, 2006, Sainsbury-Martinez et al., 2019). Recent simulations that were run to an order of magnitude longer model time than was typical show a qualitatively different flow structure for both hot Jupiters and sub-Neptunes (Mayne et al., 2017, Mendonça, 2020, Wang & Wordsworth, 2020), pointing toward the need to characterize the deep flow of gaseous exoplanets.

4.3.2 Interpreting observations with dynamical models

Numerical models of atmospheric circulation play a key role in understanding observations of exoplanet atmospheres. GCMs are uniquely suited to compare with phase curve observations, as understanding the longitudinal dependence of planetary flux requires a model for the atmospheric heat transport. GCMs have been directly compared to phase curve observations for a wide range of hot Jupiters (see Parmentier & Crossfield, 2018 for a recent review). As expected from GCM simulations, the majority of phase curves find large dayside-to-nightside temperature contrasts and eastward bright spot offsets. Additionally, GCMs have been shown to provide a good match to individual observed phase curves of hot Jupiters over a broad range of equilibrium temperature (e.g., Showman et al., 2009, Dobbs-Dixon & Agol, 2013, Zellem et al., 2014, Drummond et al., 2018, Kreidberg et al., 2018, Arcangeli et al., 2019).

Recent observations have found that the eastward hot spot offsets predicted by standard GCMs may not be ubiquitous. Dang et al. (2018) found a westward phase offset in the *Spitzer* observations of CoRoT-2b, and there is tentative evidence for westward infrared phase offsets in the atmospheres of HD 149026b (M. Zhang et al., 2018) and HAT-P-7b (Wong et al., 2016). Additionally, time-variability in the phase offset has been detected on three planets to date: HAT-P-7b (Armstrong et al., 2016), Kepler-76b (Jackson et al., 2019), and WASP-12b (Bell et al., 2019). A range of mechanisms have been proposed to explain westward phase offsets, including clouds (Armstrong et al., 2016, Parmentier et al., 2016, Powell et al., 2018), MHD effects (Rogers, 2017, Hindle et al., 2019), and non-synchronous rotation (Rauscher & Kempton, 2014).

Thanks to the sample of 26 exoplanets with observed *Spitzer* phase curves (Deming & Knutson, 2020), some of which have additional *Hubble* phase curves (e.g., Stevenson, Desert, et al., 2014, Kreidberg et al., 2018, Arcangeli et al., 2019), it is now possible to understand hot Jupiter atmospheric circulation through population-level studies. Both analytic theory (Cowan & Agol, 2011a, Perez-Becker & Showman, 2013, Komacek & Showman, 2016, X. Zhang & Showman, 2017) and GCMs (Kataria et al., 2016, Komacek et al., 2017, Parmentier & Crossfield, 2018, Tan & Komacek, 2019) predict that for hot Jupiters with equilibrium temperatures below 2200 K, the phase curve amplitude increases and the phase curve offset decreases with increasing equilibrium temperature. This is because the large-scale wave motions that drive circulation and act to induce hot spot offsets and reduce day-to-night temperature contrasts become increasingly

damped with increasing equilibrium temperature due to radiative cooling (Showman et al., 2013, Perez-Becker & Showman, 2013).

The basic expectations of the increase in the phase curve amplitude and decrease in phase offset with increasing equilibrium temperature below 2200 K appear to be borne out by observations (Cowan & Agol, 2011b, Perez-Becker & Showman, 2013, Schwartz & Cowan, 2015, Schwartz et al., 2017, Keating et al., 2019). Figure 7 shows joint constraints on the heat recirculation efficiency (which is inversely related to phase curve amplitude) and Bond albedo for the sample of observed hot Jupiters with *Spitzer*, showing an apparent decrease in the heat recirculation with increasing planetary temperature as expected from previous analytic theory. For ultra-hot Jupiters with equilibrium temperatures in excess of 2200 K, it is expected that the hydrogen that comprises the bulk of the atmosphere will become partially thermally dissociated, with a resulting net cooling on the dayside and latent heating on the nightside (Bell & Cowan, 2018). Both theoretical models (Bell & Cowan, 2018, Komacek & Tan, 2018) and GCMs (Tan & Komacek, 2019) predict that hydrogen dissociation and recombination leads to a reduction in the phase curve amplitude of ultra-hot Jupiters, with phase curve observations of the ultra-hot Jupiters WASP-103b (Kreidberg et al., 2018), WASP-33b (M. Zhang et al., 2018), and KELT-9b (Mansfield et al., 2020) showing tentative evidence for this effect. Additionally, both hot and ultra-hot Jupiters generally have low Bond albedos relative to the value of 0.503±0.012 measured for Jupiter (L. Li et al., 2018). This may suggest that silicate and other condensate clouds do not dominate the dayside optical opacity of hot gas giants to the same extent that thick ammonia clouds do so on Jupiter.

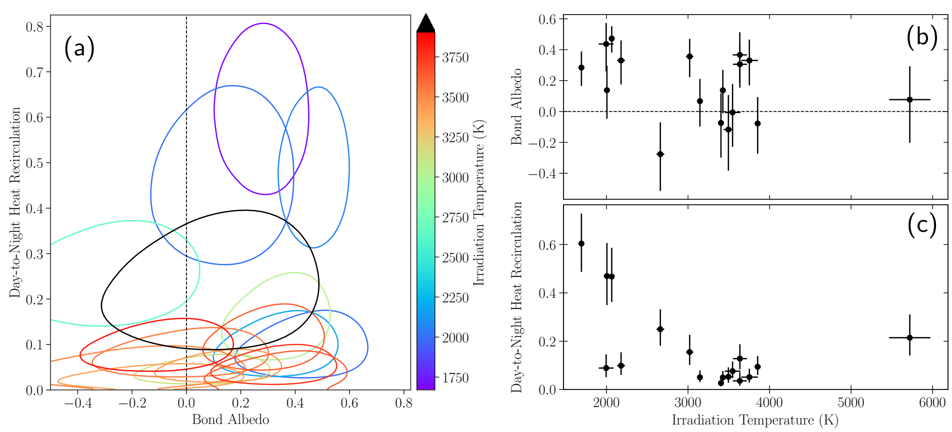


Figure 7. The atmospheric heat transport of hot Jupiters is strongly dependent on the incident stellar flux. Panel (a) shows joint constraints on day-night heat recirculation parameter (calculated as in Cowan & Agol, 2011a) and Bond albedo from literature Spitzer Channel 2 (4.5 μm) phase curve observations, where the color of each contour refers to the planetary irradiation temperature. Panels (b) and (c) show the dependence of Bond albedo and heat recirculation on the irradiation temperature. Negative Bond albedos can occur when the region probed by the Spitzer Channel 2 is a hotter-than-typical region of the atmosphere. The dayside and nightside effective temperatures and their associated uncertainties were estimated using only the published 4.5 μm brightness temperatures of Bell et al. (2020), combined with the Gaussian process regression technique of Pass et al. (2019). The inferred heat recirculation appears to decrease with increasing irradiation temperature until the regime of ultra-hot Jupiters, while there is no clear dependence of Bond albedo on incident stellar flux. Figure courtesy of Taylor Bell.

Determining if the trend in phase curve amplitude with equilibrium temperature is statistically significant requires further observations (Parmentier & Crossfield, 2018) and an improved understanding of detector systematics (May & Stevenson, 2020, Bell et al., 2020). Analysis of the growing sample of *TESS* phase curves (e.g., Daylan et al., 2019, Shporer et al., 2019, Wong et al., 2019, Jansen & Kipping, 2020, von Essen et al., 2020), unpublished *Spitzer* phase curves (Deming & Knutson, 2020), and future phase curve observations with *ARIEL* (Tinetti et al., 2018, Zellem et al., 2019) and *JWST* (Bean et al., 2018) will provide a more complete understanding of how observable properties of hot Jupiter atmospheres depend on their planetary parameters.

5 Conclusions and Prospects for Future Characterization

Hot Jupiters have been objects of intense study for 25 years, and vast strides have been made through the synergy between astronomical observations and astro- and geophysical models. There is evidence for at least two origins channels, with some hot Jupiters arriving through high eccentricity tidal migration and others through either disk migration or in situ formation. Future observations will help distinguish the importance of each channel. Better constraints on disk conditions and more detailed head-to-head comparisons on predicted occurrence rates and architectures will help distinguish whether in situ formation vs. disk migration is the predominant second channel.

The *TESS* Mission is expected to provide longer period and/or smaller targets for ground-based spin-orbit alignment measurements that will clarify the interpretation of hot Jupiters' spin-orbit alignments. *TESS* may also discover – in the mission itself or through ground-based radial-velocity follow up – more exceptional systems like WASP-47 featuring a hot Jupiter with nearby planets that likely originated through the second channel. The *Gaia* Mission will enable astrometry of hot Jupiters' companions to measure the mutual inclination and further investigations of connections between hot Jupiter occurrence and host star properties. For example, Winter et al. (2020) recently found a correlation between hot Jupiters and present-day stellar clustering. If this present-day clustering reflects the early environment, the correlation suggests that dense stellar cluster environments facilitate processes that lead to hot Jupiters. Both missions will contribute to the goal of constructing large samples of hot Jupiters with a wide range of well-constrained host star ages to determine how often hot Jupiters have already formed or arrived during the gas disk stage vs. arriving via high-eccentricity migration throughout the star's lifetime. Further theoretical study is needed to understand whether hot Jupiters' atmospheric properties can feasibly trace formation location despite the diversity of disk conditions, enabling interpretation of *JWST*'s measurements of atmospheric properties of a large sample of hot Jupiters.

In terms of planetary structure and evolution, the sheer number of planet detections means that we are firmly in the statistical era, where the large number of observed masses and radii strongly constrain evolution models. Only radius inflation mechanisms that are closely tied to the magnitude of the stellar incident flux can explain the population. Giant planet bulk metal-enrichment, as seen in the solar system, is the rule for giant exoplanets, and is itself a strongly inverse function of planet mass. Looking ahead, more detailed multi-dimensional simulations of processes that may affect the radius anomaly are needed. Additionally, detecting still more planets is definitely needed, in particular in two areas. First, a focus on hot Jupiters orbiting stars evolving off the main sequence, where the stellar forcing changes on relatively fast timescales, will give new insight into how planetary structure responds. Second, detections of planets < 1000 K around main sequence stars, below the radius anomaly threshold, is essential to understanding planetary bulk composition, to look for trends in planetary bulk composition with planetary and stellar properties (e.g., Teske et al., 2019).

In the realm of hot Jupiter atmospheres, broad trends have emerged. Albedos are typically low, due to alkali metal absorption and perhaps TiO vapor in the hottest objects. Silicate clouds appear to be an important opacity source across a wide temperature range. Trends in the day/night flux contrast are generally well-fit by models. In the near term detailed spectroscopy across a wide wavelength range with *JWST* and with large ground-based telescopes for benchmark objects is essential. It is quite likely that high-quality spectra will yield surprises in terms of atmospheric abundances and trends with planet mass and temperature. Entirely new paradigms may well emerge. Later, the field will move to the statistical assessment of exoplanet atmospheres with the European Space Agency's *ARIEL* mission. This must be done in tandem with a hierarchy of modeling approaches, including those based on solar system and exoplanetary expertise. This is because we have likely only glimpsed at the true 3D nature of these atmospheres, and future observations will push models toward even higher levels of complexity. Very soon, *JWST* and high-resolution ground-based observations of the lower and upper atmosphere in transmission and emission will also pay large dividends in understanding atmospheric composition, circulation, and escape.

Appendix A Glossary

Astrometry: The measurement of the positions, motions, and magnitudes of stars, which enables a measurement of their distance.
Atmospheric column mass: Mass per unit area of the atmosphere, equal to p/g, where p is the atmospheric pressure and g is gravity.
Bayesian: A statistical approach that uses Bayes' theorem to assign probabilities to events that are updated based on new data.
Bond albedo: The fraction of the total incident electromagnetic radiation upon a planet that is scattered back to space.
Corotation period: Orbital period of a planet at which its orbital period is equal to the stellar rotation period.
Double-diffusive convection: A form of convection driven by two different density gradients with separate diffusivities.
Embryo: A rocky building block of planets that is larger than $\sim$ 1000 km in diameter.
Hydrostatic equilibrium: An atmosphere in which the force due to the decrease in pressure with height balances gravity.
Ionization potential: Energy necessary to remove an electron from a neutral atom.
Irradiation temperature: The temperature that the planet would have on the star-facing side if there were no horizontal heat transport. The irradiation temperature $T_{\rm irr}$ is related to the zero-Bond albedo equilibrium temperature $T_{\rm eq}$ as $T_{\rm irr} = 4^{1/4} T_{\rm eq}$.
Kozai-Lidov cycles: An orbital cycle between the eccentricity and inclination that caused by the perturbation of a distant third body.
M star: The smallest and coolest type of star, with effective temperatures below 3900 K.
Magnetocavity: The innermost region of the proto-planetary disk that is cleared out due to truncation by the stellar magnetic field.
Magneto-hydro-dynamics (MHD): The study of the motions of electrically conducting fluids.
Metallicity (astrophysical): Abundance of elements that are heavier than hydrogen and helium.
Migration: The radial movement of the orbit of a planet due to interactions with a disk or other planets.
Navier-Stokes equations: A set of differential equations that can be applied to study the motions of geophysical fluids.
Ohmic dissipation: Transfer of electrical energy to thermal energy when current flows through a resistance.

Opacity: The amount of absorption and scattering of incident electromagnetic radiation by a material.
Pebbles: Centimeter to meter sized particles in proto-planetary disks that undergo radial drift due to gas drag.
Phase amplitude: Difference between the maximum and minimum observed emergent planetary flux over a full orbital phase.
Phase offset: Shift in orbital phase between secondary eclipse and the maximum observed emergent planetary flux.
Photoionization: The loss of an electron from an atom or molecule due to absorption of electromagnetic radiation.
Planetesimal: Solid body that forms during the era of planet formation that is larger than ~ 1 km.
Proto-planetary disk: A disk of gas and dust that surrounds a young star.
Radial Velocity: A method used to detect planets by observing the periodic effect that the gravity of a planet causes on the location of spectral lines of the host star.
Refractory: A solid material that is resistant to becoming gaseous at high temperatures.
Secular: Taken or averaged over many orbits.
Shear instability: A dynamical instability that occurs when there is sufficient velocity shear in a fluid.
Substellar point: The point on a planet's surface where the host star is directly overhead and incident rays of light from the host star strike perpendicularly to the surface.
Superrotation: A phenomenon that occurs when a planetary atmosphere has greater angular momentum than the solid-body rotation of the interior.
T Tauri star: Pre-main-sequence stars that vary in their emitted light and are less than ~ 10 Myr old and still contracting.
Transit: A method of detecting planets by observing the periodic decrease in stellar brightness due to the planet blocking light from the host star.
XUV: An acronym for Extreme UltraViolet radiation, which is light with wavelengths between $\sim 0.1 - 0.01\mu$m.
Zero Bond albedo equilibrium temperature: The temperature a planet would have assuming that it does not reflect any incident stellar radiation and perfectly redistributed heat across its surface, equal to $[F_\star/(4\sigma)]^{1/4}$, where $F_\star$ is the incident stellar flux and σ is the Stefan-Boltzmann constant.

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